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Discrete particle simulation for high-density crowd

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Abstract

The present paper describes the discrete particle simulation of the evacuation dynamics. The inter-pedestrian forces are given by the discrete element method (DEM). The composite particle model is proposed to take into account the effect of the non-circular shape of pedestrians on the evacuation behavior. It has been indicated that the pedestrians can evacuate faster when an obstacle is placed at an appropriate position. The effect of the obstacle on the evacuation rate is also examined numerically in the present study. The proposed numerical model represents the positive and negative effects of the obstacle on the evacuation behavior qualitatively.

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Keywords: numerical simulation ; discrete element method ; evacuation ; high-density crowd ; composite particle model ; obstacle

1. Introduction

Pedestrian dynamics has drawn attentions of many researchers in recent years. In addition to the experimental contributions (Hoogendoorn et al. (2003) ; Helbing et al. (2007)), many numerical approaches, such as a cellar automaton (Yanagisawa et al. (2009)), multi-agent simulation (Kaneda, 2005), social force model (Helbing et al. (2000)), and so on, have been applied to the pedestrian flows. DEM (discrete element method), which had been developed in the civil engineering to simulate the motion of soils (Cundall et al. (1979)), has also been applied to the pedestrian flows recently (Tsuji (2003); Gotoh et al. (2012)). DEM is applicable to highly dense situations, since it can conduct the multiple contacts of particles.

The behavior of pedestrians at an exit is one of the most substantial issues, since it is the rate-determining step during the emergency evacuations. The exit is a bottleneck to cause jams of pedestrians. Especially, the arching of

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pedestrians is strongly related to the deterioration in the efficiency of evacuation. It has been suggested that an obstacle placed in front of the exit suppresses the arching to reduce the evacuation time (Nishinari et al, 2008).

In the present paper, the evacuation from an exit is numerically studied by use of DEM. A composite particle model is proposed to take into account the shape of the human body, that is, the shoulder width is wider than the chest depth. The effect of an obstacle placed in front of the exit on the evacuation dynamics is also studied.

Nomenclature

F_C	contact force [N]
F_G	gravitational force [N]
I	moment of inertia [kg m^2]
k	spring constant [N/m]
m	mass [kg]
t	time [s]
T	torque [N m]
v_r	relative surface velocity [m/s]
x	position [m]
δ	deformation [m]
η	damping coefficient [N s/m]
μ_f	coefficient of friction [-]
ω	angular velocity [1/s]

subscript

n	normal direction
t	tangential direction

2. Model description

A dynamics-based particle model is employed to simulate the pedestrian motion. In highly crowded conditions, a pedestrian may contact with multiple other pedestrians at the same time. Thus, the soft sphere model rather than the hard sphere model is suitable to express the inter-pedestrian forces.

DEM (discrete element method), which is one of the soft sphere models, is adopted to model the inter-pedestrian forces in this study. The contact force model of the DEM is schematically shown in Fig. 1(a). The elastic property of the human body at the compaction in the crowd is expressed by a spring. A damper represents the dissipation of energy during the contact. The elastic and the frictional properties in the tangential direction can be expressed by a spring and a slider.

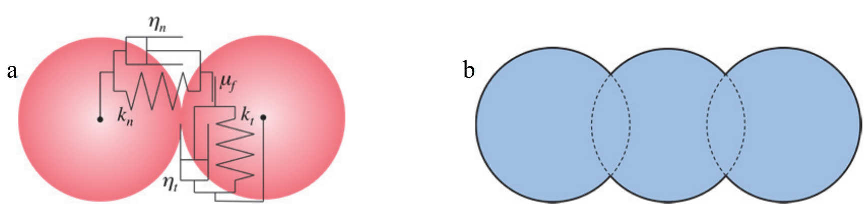

Fig. 1. (a) contact force model of DEM; (b) composite particle model.

The translational and the rotational motion of pedestrians are described by the following Newton's equations of motion.

$$\frac{d^2\vec{x}}{dt^2} = \frac{\overrightarrow{F_G} + \overrightarrow{F_C}}{m} \tag{1}$$

$$\frac{d\vec{\omega}}{dt} = \frac{\vec{T}}{I} \tag{2}$$

where, F_G is the gravitational force, F_C is the inter-pedestrian force due to physical contact, m is the mass of a pedestrian, ω is the angular velocity, T is the torque and I is the moment of inertia. The contact force in the normal direction is given by the following equation.

$$F_{Cn} = -k_n\delta_n - \eta_n v_{rn} \tag{3}$$

where, k_n is the normal spring constant, δ_n is the deformation in the normal direction, η_n is the normal damping coefficient and v_{rn} is the normal component of the relative surface velocity between contacting pedestrians.

The contact force in the tangential direction is given as follows,

$$F_{Ct} = \min\left[-k_t\delta_t - \eta_t v_{rt}, \mu_f F_{Cn}\right] \tag{4}$$

where, k_t is the tangential spring constant, δ_t is the relative tangential deformation of the contacting pedestrians, η_t is the tangential damping coefficient, v_{rt} is the tangential component of the relative surface velocity between contacting pedestrians and μ_f is the coefficient of friction. The notation min[A,B] means that the smaller value of the magnitude of A and B is chosen. The first part in the bracket corresponds to the static friction, and the second part the dynamic friction.

A circular shape is advantageous in the detection algorithm of inter-particle contact. The top view of human body, however, is not circular: the shoulder width is wider than the chest depth. Therefore, a composite particle model shown in Fig. 1(b) is proposed to express the non-circular shape of the human body. In the present composite particle model, three particles are rigidly stuck with arbitrary overlaps.

Further, a resistance torque and a remote spring are introduced in the present calculation (Fig. 2). The former is the torque acting on the pedestrian depending on the angle deviation to keep the pedestrian facing to the destination. The latter is the virtual spring acting on the pedestrian from other pedestrians within the specific distance and angle of visibility prior to the physical contact. Thus, the pedestrians tend to avoid physical collisions with other pedestrians, walls or the obstacle.

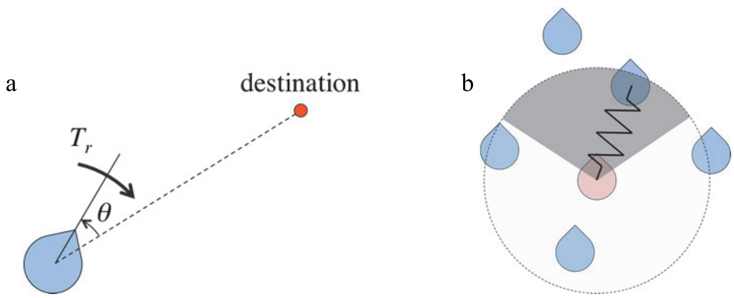

Fig. 2. (a) resistance torque; (b) remote spring.

3. Results and discussions

3.1. Calculation conditions

2D calculations of the evacuation from a 5 m X 5 m rectangular room with an exit of 900 mm width are performed. 40 persons are randomly distributed in the room initially. A composite particle consists of 3 primary particles with 200 mm in diameter. The shoulder width and the chest depth are 500 mm and 200 mm, respectively. Thus, the neighboring primary particles are allowed an overlap of 50 mm with each other. The mass of a pedestrian is 60 kg. All persons walk to the exit with the speed of 1.0 m/s. Other parameters used in the DEM calculation are summarized in Table 1.

Table 1. Parameters in DEM.

Spring constant	100000	N/m
Damping coefficient	350	N s/m
Coefficient of friction	0.0	
Time increment	0.001	s
Angle of visibility	120	degree

3.2. Evacuation behavior

Typical sequential snapshots of 40 persons evacuating from an exit are shown in Fig. 3. The exit width of 900 mm is less than twice the shoulder width. Therefore, only one pedestrian can evacuate from the exit at the same time if all the pedestrians face exactly to the exit. It can be observed that the pedestrians tend to twirl their body when they pass through the crowded exit. The arching was observed at some instances, which lengthen the total evacuation time.

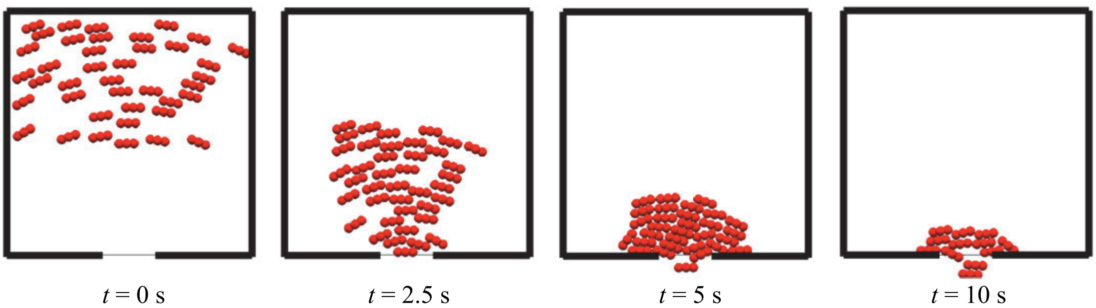

Fig. 3. Sequential snapshots of evacuation behavior (without obstacle).

A circular obstacle with 1.2 m in diameter is placed in front of the exit. The center of the obstacle is 1.0 m apart from the exit (y = 1.0 m), which means that the interstices between the edge of the exit and the obstacle are 497 mm ; approximately the same size as the shoulder width of the pedestrian. Typical sequential snapshots are shown in Fig. 4. It was observed that the pedestrian behavior at the exit became smoother than that in Fig. 3. The obstacle suppresses the formation of arching at the crowded exit. Thus, the obstacle has a positive effect on the evacuation behavior in this case.

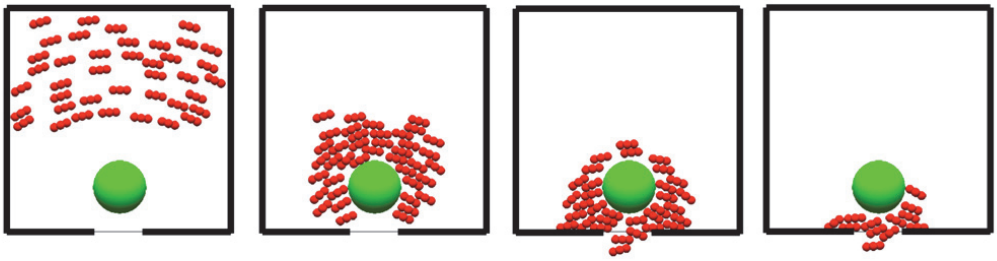

Fig. 4. Sequential snapshots of evacuation behavior (with obstacle at y = 1.0 m).

Fig. 5 shows typical sequential snapshots when the obstacle is placed at the closer position (y = 0.81 m), in which the interstices between the edge of the exit and the obstacle are 327 mm. The jamming of pedestrians takes place at the exit, which means that the obstacle disrupts the pedestrian flow at the exit in this case. Thus, the obstacle has a negative effect on the evacuation behavior when it is placed too close to the exit.

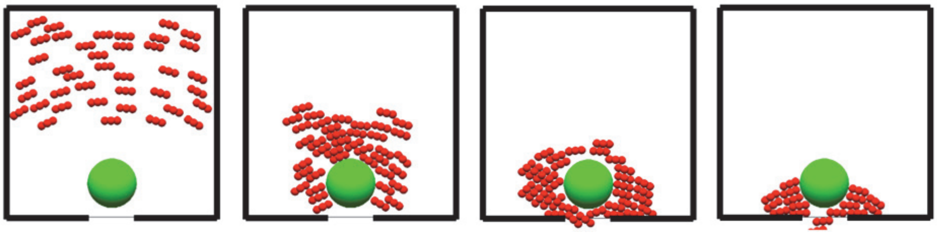

Fig. 5. Sequential snapshots of evacuation behavior (with obstacle at y = 0.81 m).

The temporal variation in the number of remaining persons in the room is shown in Fig. 6 for the case (a) without obstacle, (b) with obstacle at y = 1.0 m and (c) with obstacle at y = 0.81 m. In order to confirm the reproducibility, calculations are performed more than 20 times for each case for different initial distribution of pedestrians. The temporal variations for representative 5 trials are plotted in Fig. 5. The average and the standard deviation of the total evacuation time for each case are summarized in Table 2. The obstacle at y = 1.0 m reduces the total evacuation time more then 1 second compared to the case without obstacle. On the other hand, the obstacle at y = 0.81 m lengthen the total evacuation time more than 2 seconds. That is, the obstacle placed in front of the exit may have positive and negative effects on the evacuation behavior. When it is placed at the appropriate position, the arching is suppressed and the total evacuation time is reduced. When it is placed too close to the exit, however, the pedestrian flow is disrupted and the total evacuation time becomes longer.

Table 2. Evacuation time.

	average [s]	standard deviation [s]
(a) without obstacle	14.32	1.57
(b) with obstacle at y = 1.0 m	12.94	0.97
(c) with obstacle at y = 0.81 m	16.63	0.98

4. Summary

DEM simulations with the composite particle model are applied to the evacuation dynamics. The effect of an obstacle placed in front of the exit is studied numerically. When the obstacle is placed at an appropriate position, pedestrians can evacuate faster compared to the case without obstacle. When the obstacle is placed too close to the exit, on the other hand, the pedestrian flow is disrupted and the total evacuation time becomes longer than the case without obstacle. The present numerical model can simulate the effect of the obstacle on the evacuation behavior qualitatively.

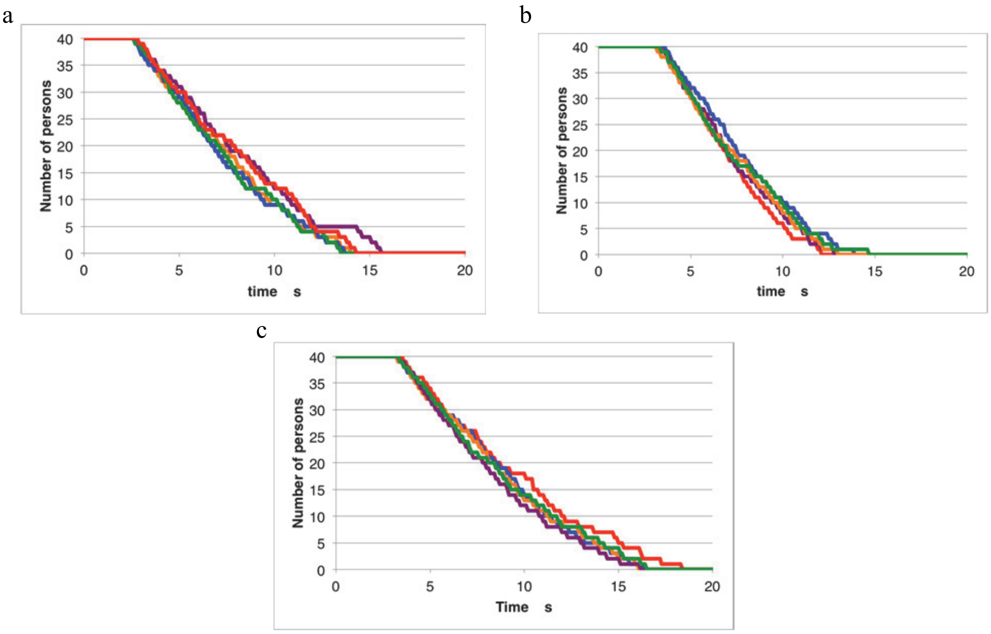

Fig. 6. Temporal variation in number of remaining persons (a) without obstacle; (b) with obstacle at y = 1.0 m; (c) with obstacle at y = 0.81 m.

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